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AN EXPERIMENTAL ANALYSIS
OF A MILD WEAR PROCESS

ROY FRANKLIN BARRETT
AND
JOSEPH ALROY GILDEA

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OF A

MILD WEAR PROCESS

by

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1958

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SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1958

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by

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Submitted to the Department of Naval Architecture and Marine Engineering on 26 May 1958 in partial fulfillment of the requirements for the degrees of Naval Engineer and Master of Science in Naval Architecture and Marine Engineering.

ABSTRACT

The physical processes that occur during a sliding process are very complex. In order to isolate some of these mechanisms, experiments were conducted using radioactive and inert, mild-steel pins wearing on a rotating hardened steel ring. These results, obtained under several different operating conditions, were then used to check the validity of a theoretical equation, derived through a statistical analysis of the behavior of sliding contacts. It was demonstrated that such an analysis can be used to interpret experimental results of this kind of wear and metal transfer tests.

During the performance of these experiments, it was verified that the pin wear rate remained constant throughout each test.

The major role that oxidation plays in both the rate of wear from the pin and the rate of mass transfer to the ring, was shown by these experiments.

With an increase in speed, a critical point was reached where no material worn from the pin stayed on the ring. This was attributed to the high local temperatures which caused immediate oxidation and rubbing away of any transferred material.

Below this critical speed, it was found that, within experimental error, the total amount of mass transferred to the ring was independent of both load and speed.

Thesis Supervisor: Brandon G. Rightmire

Title: Associate Professor of Mechanical Engineering

Cambridge, Massachusetts
May 26, 1958

Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

In accordance with the requirements for the Degrees of Naval Engineer and Master of Science in Naval Architecture and Marine Engineering, we herewith submit a thesis entitled "An Experimental Analysis of a Mild Wear Process."

Respectfully,

Roy Franklin Barrett
Lieutenant, United States Navy

Joseph Alroy Gildea
Lieutenant, United States Navy

ACKNOWLEDGEMENT

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I. INTRODUCTION

Much experimental work has been done to determine the relationship of variables during a sliding process between two dry unlubricated steel surfaces. Kerridge (1955), using radioactive tracer methods, has established that the wear mechanism is a three stage process involving transfer of metal, its conversion to oxide and the removal of the oxide to give a loose wear product.

A theoretical treatment of this kind of wear process by a statistical analysis of the behavior of sliding contacts has been proposed by Rightmire (1957). He classified all the contacts, formed under steady conditions, in accordance with some characteristic such as area at the instant of observation, or the mass transferred from one member to the other during the life of the contact. As a result he determined a constant relationship between the number of contacts which produce transfer and the total number of contacts. Next, from the experimental results of Kerridge, he deduced a relation between the same two factors. Inserting experimental values into this relation the constant was found to be practically equivalent to that determined theoretically by statistics. Equating these he found an expression relating the variables of this wear and transfer process. This equation is:

$$\frac{4 W}{\rho \pi D \alpha b y} = 1 \quad (1)$$

where

W	= wear per revolution
ρ	= density of pin material
D	= diameter of ring

b = width of pin normal to sliding direction

y = thickness of transferred layer

$$\alpha = - \left[\frac{\partial^2 (m/2r)}{\partial z^2} \right]_{z = \Delta z} \quad (2)$$

z = revolutions of the ring

m = mass of material transferred from a pin

remaining in the transferred layer after z

revolutions of the ring

The factor α will be described and determined in later sections.

To check some of the conditions under which this equation is valid is the purpose of this paper.

II. PROCEDURE

The equipment used for these tests was a bench lathe adapted as a simple pin and ring apparatus illustrated in Figures I and II. The mild steel test pin was held in a loading arm which pivoted on ball bearings to allow accurate realignment after swinging the arm away for removal of the face-plate. This face-plate supported a hardened steel bearing cup which acted as the cylindrical rotating surface. The lathe, driven by a variable speed Graham drive and housed in a positive draft hood, was controlled either by a preset counter automatically stopping the lathe after a desired number of revolutions or by stopping it after a desired length of time. The operating atmosphere was controlled by a shield surrounding the cylindrical surface during the test and to which was connected a supply of dry, oil-free, compressed air. This air was led from the tank through a sodium hydroxide dehumidifier, a flow indicator, and then a copper coil immersed in liquid nitrogen to ensure that no moisture remained in the operating atmosphere. (Figure III)

In an experiment the procedure was to run the pin and ring together for a desired time, then remove the pin for weighing on a Seederer-Kohlbusch chemical balance to indicate the amount of wear. In this way the wear rate of the pin was determined. To measure the amount of transfer from the pin to the ring a radioactive pin of the same material as the inert pin was run on the ring. Then the face-plate with the ring was removed from the lathe and placed on a vertical spindle which rotated the ring at a constant speed before a Geiger-Muller tube. This entire assembly was placed within a lead castle as shown in Figure IV. This

lead greatly reduced the background activity. The Geiger-Muller tube, positioned 1/16 inch from the ring, and its attendant scaler recorded the counts per minute produced by the mass of transferred radioactive material. This count was compared with the count produced by a known mass deposited on a similar ring as described in Appendix A. In this manner the amount of mass transferred during the test was calculated.

Before each test the speed of the lathe was carefully checked with a tachometer. Both the pin and cylindrical surface were cleaned with two applications of benzene to remove any oil and then given a final surface finish with 4/0 abrasive to remove the benzene film.

The pins were made radioactive by pile irradiation at the Brookhaven National Laboratory. The method for calculating the amount of activity desired and the length of time for irradiation is presented in Appendix B.

An analysis of the mild steel pin material showed the following composition:

Carbon	.13%
Phosphorus	.08%
Sulphur	.22%
Manganese	.90%
Silicon	.01%
Iron	98.66%

These pins were made from $\frac{1}{4}$ " x $\frac{1}{4}$ " stock with a hardness of 98 Rockwell B. The rings were Timken Bearing cups #3623 OD 2.5 in., width .6875 in. Their hardness was 62 Rockwell C.

III. RESULTS AND DISCUSSION

Throughout this series of experiments to obtain wear and mass transfer data under different operating conditions, the theory of wear, as a three stage process, advanced by Kerridge (1955) was seen to be verified. These data were then reduced to the form required by the theoretical formulation of Rightmire (1957) in Equation (1).

WEAR RATE

Experiments were run under three different loads 250, 500 and 1000 grams at 542 RPM (180 cm/sec). Speeds of 270 RPM (90 cm/sec) and 750 RPM (249.5 cm/sec) were also used with a 500 gram load. As anticipated from basic wear theory, the wear varied with the load. This is shown in Figure XXIII. This marked decrease in the wear rate with a decrease in load may be explained by considering the individual contacts between the surfaces. Under a light load a greater percentage of these contacts remain within their elastic limit, receiving no permanent deformation and associated wear. Further investigation into the effects of very light loads on the wear rate should be conducted.

Under a constant load, a change in the speed caused an inverse variation in the wear rate as shown in Figure XXIV. Many sources, as reference (6), describe the sliding process between two unlubricated surfaces as the formation and shearing of small bridges at the tips of prominent asperities of the surfaces. If this assumption is made one would expect that at the lower speeds two such asperities would meet less frequently than at higher speeds. Therefore between the occasions of actual contact, more time would be available for oxidation of the

contact points. As will be demonstrated in a later section by experiments, this oxidation over a longer period does, in fact, cause a definite increase in the wear.

As seen in the plot of each test, the wear rate for that test was found to be a constant. This is in accord with Kerridge but is different from that of reference (7) which reported a definite transition point from a lower to a higher wear rate.

An interesting result noted during the experiments was the effect on the wear of varying the length of operating time between wear measurements. A higher wear rate was found when the wear was checked at short intervals rather than running the test for the same total time continuously. This probably can be attributed to the oxidation of the worn surface while the measurement was being made. This oxidized material, at the resumption of the run, was then readily worn away. Under continuous operation this oxidation could not occur.

MASS TRANSFER

Upon running the pin against a ring for a length of time dependent on the load and speed, the amount of material transferred to the ring reached a point of equilibrium. At this time the track on the ring appeared practically solid and the mass of material, as shown by radioactive methods, remained constant regardless of the length of time the experiment was continued. The mechanism which controls this is that described by Kerridge (1955) as the wearing away of oxidized material at the same rate that new material is being transferred to the track.

When an equilibrium layer had been attained on a ring using an inert pin, the latter was replaced with an active pin to show the rate

of this exchange of material. This is shown in Figures VIII, XI, XIV, XVII and XX for various operating conditions. The initial rate of increase of the amount of active material is a measure of the equilibrium transfer rate since, at this stage, activity is being transferred to the layer while only inactive material is being worn off. As the proportion of active material in the equilibrium layer increases, the proportion worn off also rises similarly. The rate of conversion of an inactive to an active layer therefore lessens.

EFFECT OF SPEED

As the speed of the ring was increased with a constant load, it was found that there was a point where the material worn from the pin did not show any observable transfer to the ring. Under a 500 gram load at 750 RPM a complete, uniform track was formed on the ring. With the same load at 1000 RPM for the same length of operating time there was no noticeable transfer. At the median speed, 875 RPM, there was a very slight patchy transfer. This indicated a transition point between 750 and 875 RPM.

This can possibly be attributed to the high temperature caused locally as a result of the frictional work. This temperature caused the transferred material to oxidize immediately and the oxide, not being adherent, was rubbed off without effecting any observable transfer.

Another process that may be happening concurrently, as the temperature rises, is the reduction in friction, as incipient melting begins on the tips of contacting asperities. This film, resulting from the melting, could resemble that of a lubricant film by reducing friction, causing smoother sliding and protecting the underlying surfaces. Further

tests should be conducted, using a radioactive pin at these high speeds, to better explain the actual mechanism that is controlling the reduction in mass transfer.

As noted through the discussion thus far, oxidation is a major factor in both wear and mass transfer. This oxidation can result from:

1. stopping the experiment for wear measurement
2. the length of time between contact of the asperities during low speed operation
3. the high local temperatures at high speed operation.

EQUILIBRIUM TRANSFERRED LAYERS

As shown in Figure XXVI the limiting value of the mass transferred during tests with a constant speed was practically independent of the magnitude of the load. For the three different loads the equilibrium mass transferred varied between 1.9 mg and 2.4 mg.

Under a constant load and with a variation of speed, the only value outside this range was found at the highest speed used, (750 RPM). This value, 1.5 mg, was obtained near the speed where the high local temperatures drastically affect the mass transfer.

In general then, under similar operating conditions and outside the range of speeds where high friction temperatures predominate, it was found that the equilibrium amount of mass transferred was independent of both load and speed.

Illustration of the Use of Experimental Data in the Theoretical Equation

In Equation (1) the equilibrium wear rate, ($2r$), was established by using the average of the entire run during which wear measurements were made.

A mean thickness, (y) , of the transferred material was computed from the value of the apparent contact area (width of the pin times the diameter of the ring), the amount of material transferred on the ring, and the density of the pin material.

The ratio, $\left(\frac{m}{2r}\right)$, of the mass of active material transferred and remaining in the layer to the equilibrium wear rate, was plotted as ϕ against the coordinate Z , total revolutions. These plots are shown in Figures IX, XII, XV, XVIII, and XXI. The first derivative or slope, $\left(\frac{\partial \phi}{\partial Z}\right)$, of these is plotted in Figures X, XIII, XVI, XIX, and XXII. The term α , which is the slope of the latter curves at $Z = \Delta Z$ is shown for one test on Figure X. The value $Z = \Delta Z$ is the one at which $\frac{\partial \phi}{\partial Z}$ ceases to be a constant. All differentiation for these plots was done graphically. The theory underlying this derivation can be obtained in references (2) and (3).

Equation (1) indicates that a certain product of these factors should be equal to unity. For the first five experiments the values obtained were:

TABLE I

Load (grams)	Speed (RPM)	Value of product
1000	542	.899
500	542	.26
250	542	.017
500	270	.228
500	750	.079

The variation in the value of the product is quite large. However the vast divergence between a theoretical derivation and an experimental

approach, with its many possible sources of error, could introduce deviations of this magnitude.

In the first five experiments a newly refaced inert pin was run on the ring to form the equilibrium layer and then each time a newly refaced active pin was inserted to perform the mass transfer experiments. During these tests it was found that the initial mass transfer rate was considerably higher than the average wear rate. It was the aim of the last tests, with a load of 500 grams operating at 542 RPM, to investigate the influence of using a worn pin instead of a new pin in each of these cases. With a worn pin wearing on a fresh ring, the initial wear rate was found to be lower. A possible explanation is that the apparent contact area between the pin and the ring is essentially a line. Of the total area of this line a greater percentage is comprised of actual contact points than in the case of the worn pin where the apparent contact area extends for some distance in the direction of rotation. Therefore the contacts of the line were rubbed more frequently than those of the larger apparent contact area.

A comparison of the rate of mass transfer was then made between the use of a fresh pin and the use of a pin already showing a wear scar on its face. As shown in Figure XXVII, the worn pin gave a lower rate of replacement of the inactive material with active material. This can be explained in the same manner as the lower wear rates with a worn pin. As the initial wear rate is lower, the initial mass available for transfer is also lower.

With a decrease in the value of the mass transfer, (m) , it will approach the value of the initial wear rate. This will reduce $\phi, \left(\frac{m}{2r}\right)$,

as in Figure XXVIII with a concurrent reduction in its slope, $\left(\frac{\partial \phi}{\partial z}\right)$, as in Figure XXIX. α , which is obtained from the curve of the slopes of ϕ , will therefore be reduced. Introducing this into Equation (1) will give an overall increase in the value of the constant as listed in Table I.

It is felt from the above reasoning that the use of pins, worn to the curvature of the rotating ring, before actual use in a test, will produce results that are more in conformance with those predicted in the theoretical equation.

In summary, the results of these experiments corroborate Kerridge's theory of this wear process. For each operating condition the wear rate was found to be a constant value. Oxidation plays an important role in the initial wear and mass transfer rates.

As was the purpose of these tests, it was shown for several different operating conditions, a theoretical statistical analysis can be used to interpret the physical processes accompanying the sliding of one unlubricated surface over another. Continued experimentation in this direction may lead eventually to the ability to accurately predict the interplay of the variables and processes which accompany the movement between two such surfaces.

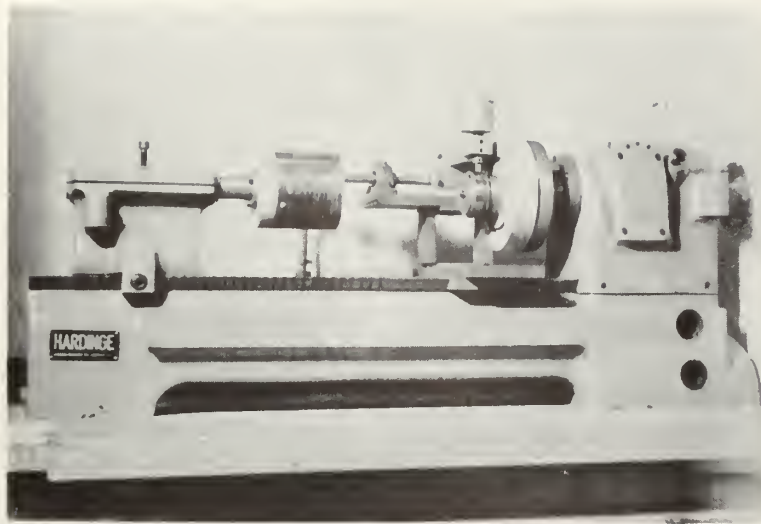


Figure I Lathe with the cylinder and the pin; at left is the atmospheric shield that encloses the cylinder when running the experiments.

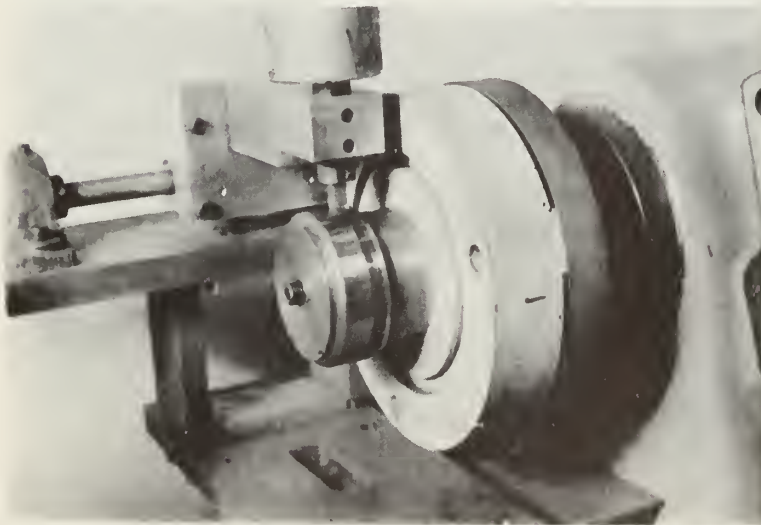


Figure II Detail of the cylinder and pin loading device.

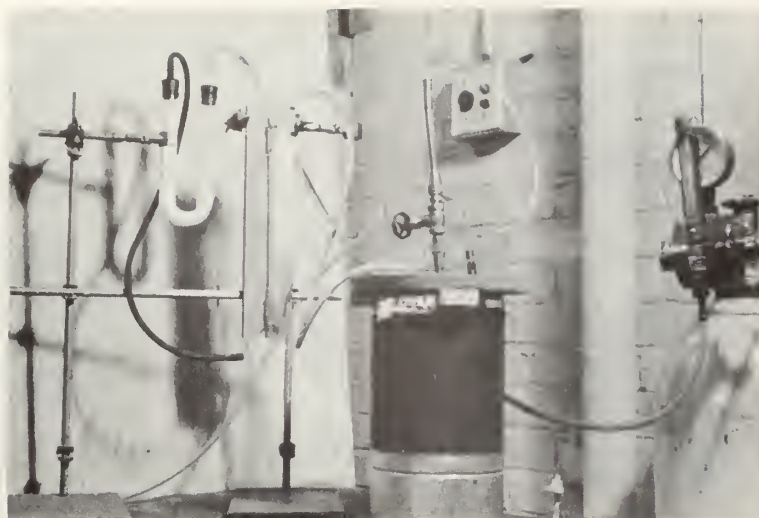


Figure III Atmospheric Supply.

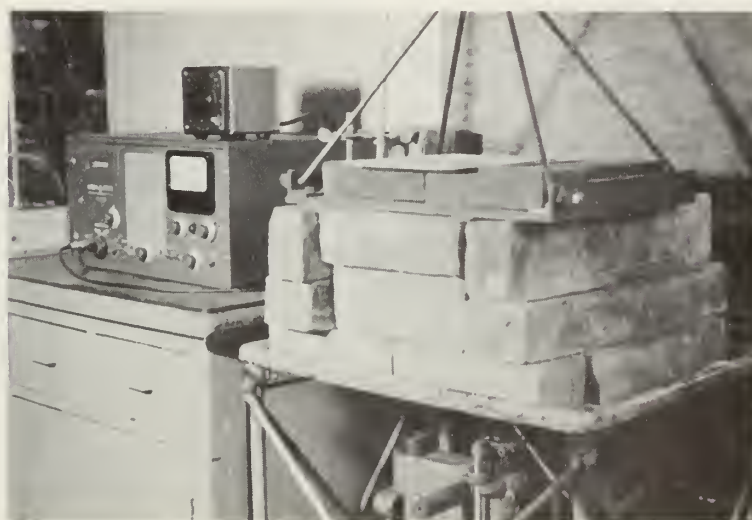


Figure IV Lead castle; at right enclosure of lead blocks over rotating support inside of which is the cylinder and Geiger tube; at left the scaler.

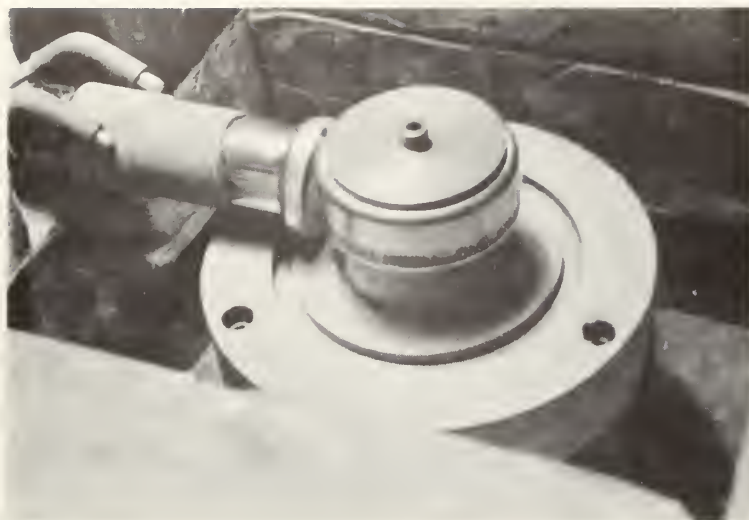


Figure V Detail of the cylinder with the radioactive track and the Geiger tube. This view is inside the lead block enclosure. The rotational axis of the cylinder is vertical.



Figure VI Detail of radioactive standard.



Figure VII Radioactive Standard Assembled.

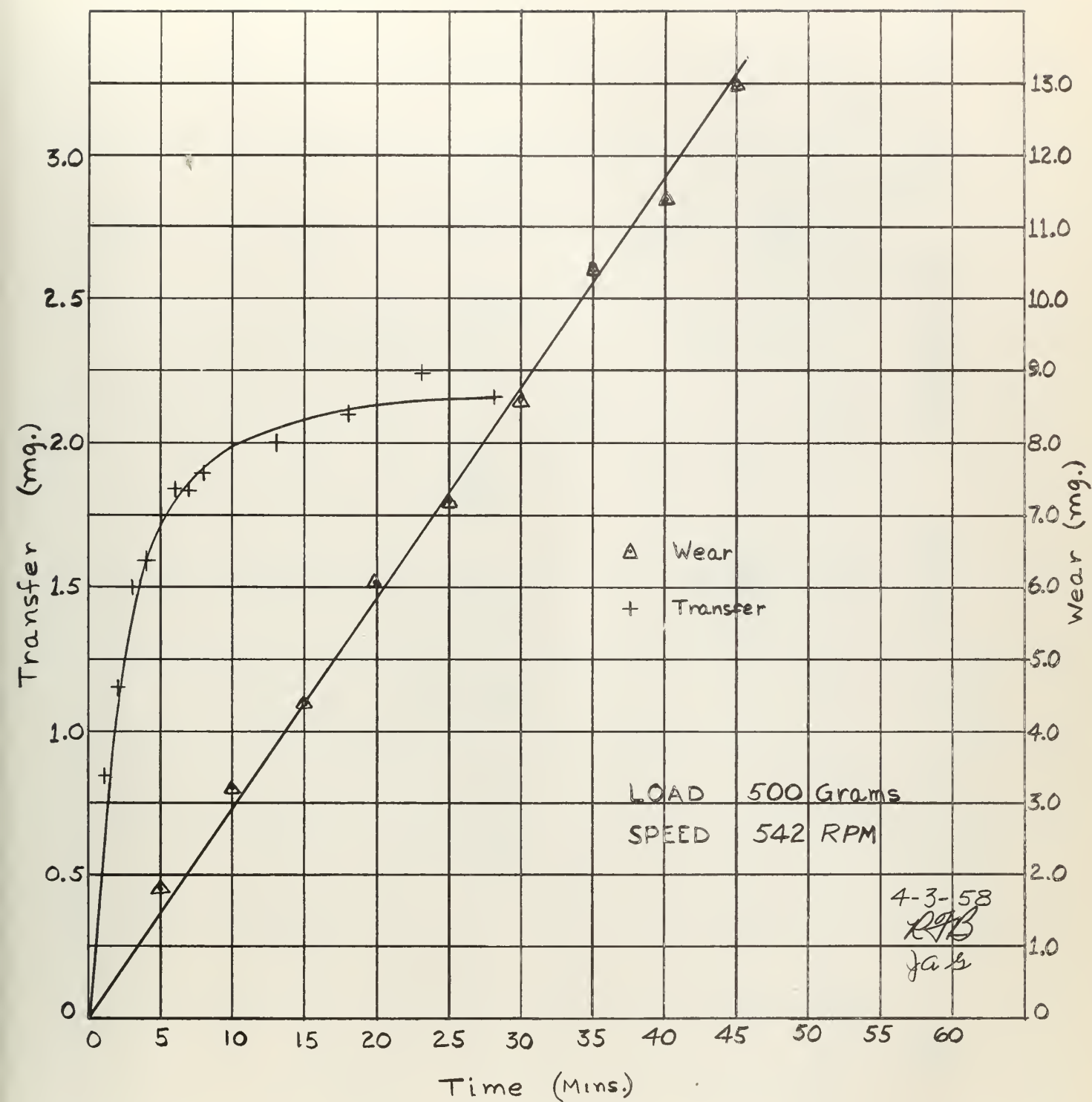


Figure VIII. Wear And Metal Transfer

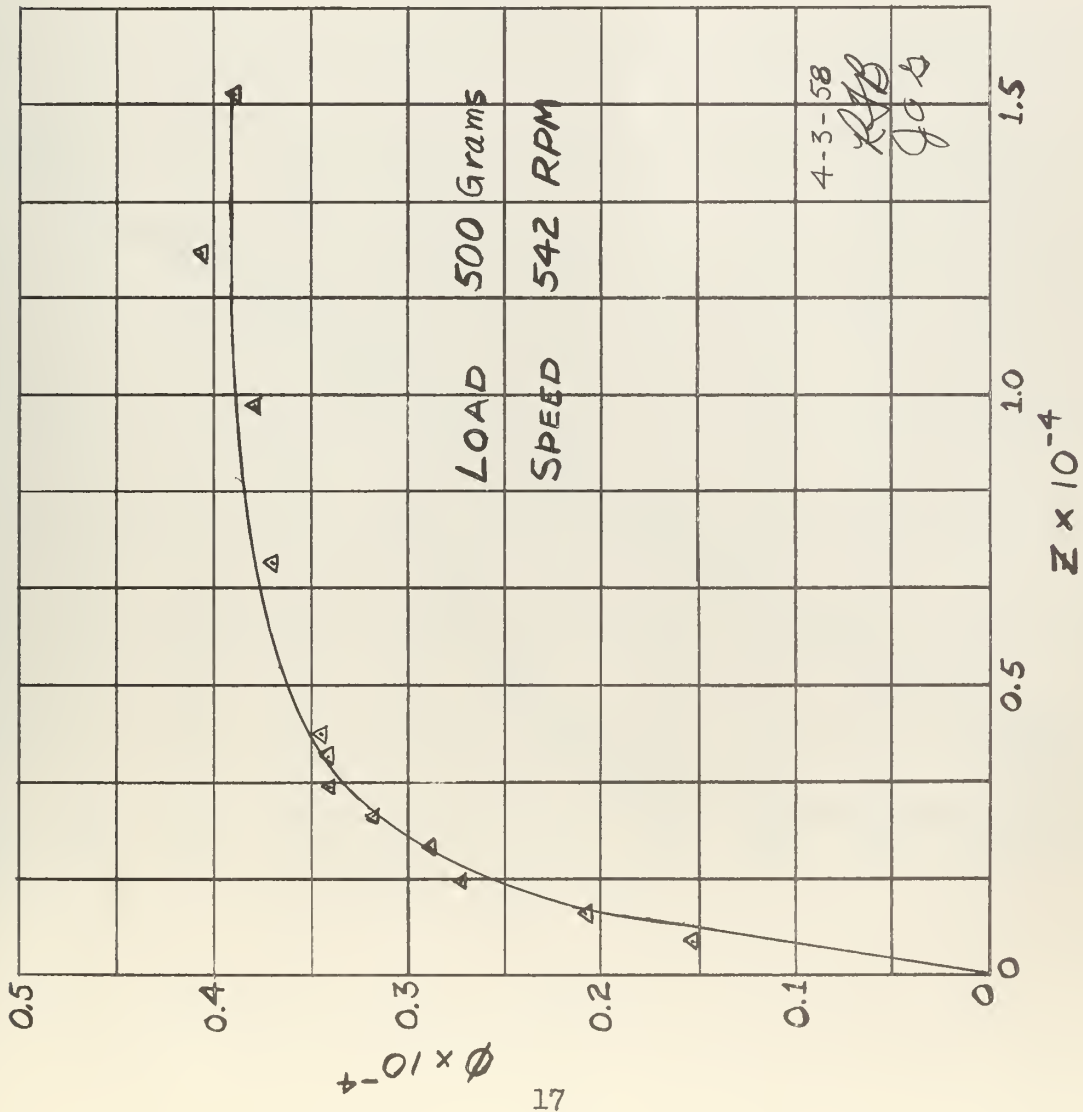


Figure IX. Dimensionless Form of Wear and Metal Transfer.

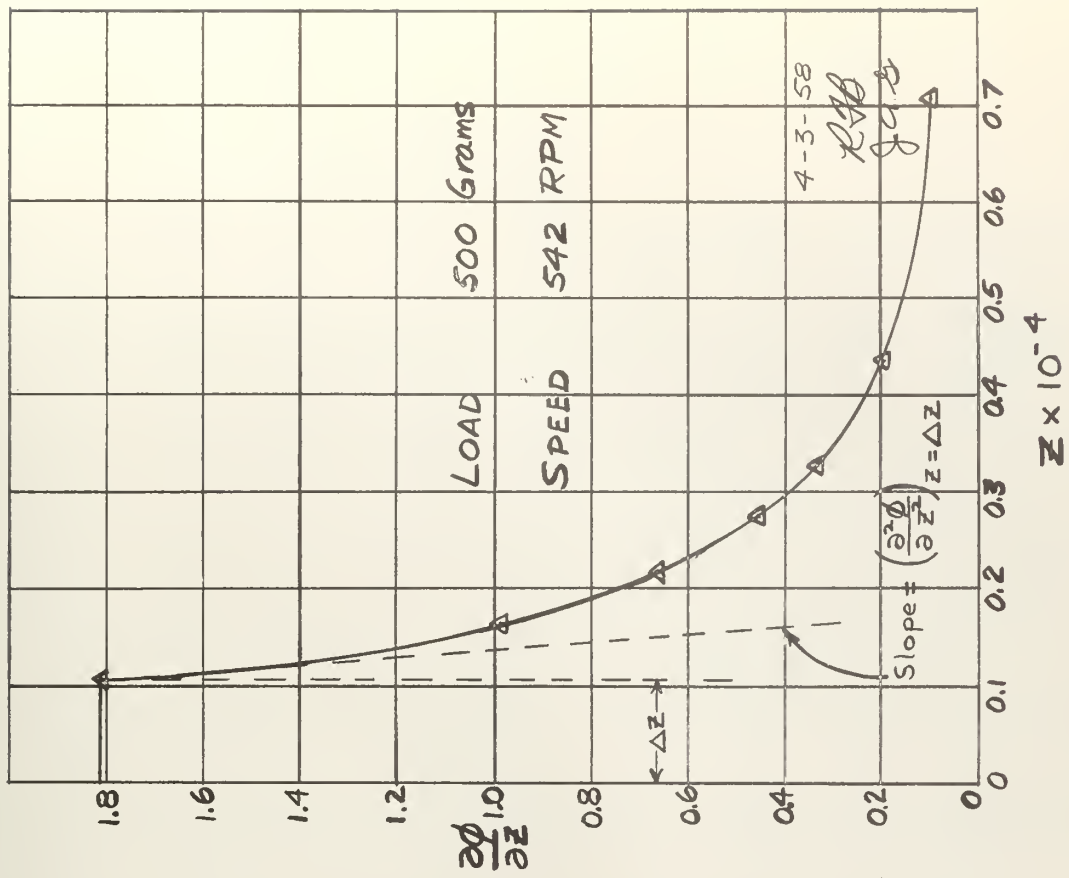


Figure X. Slope of Figure IX

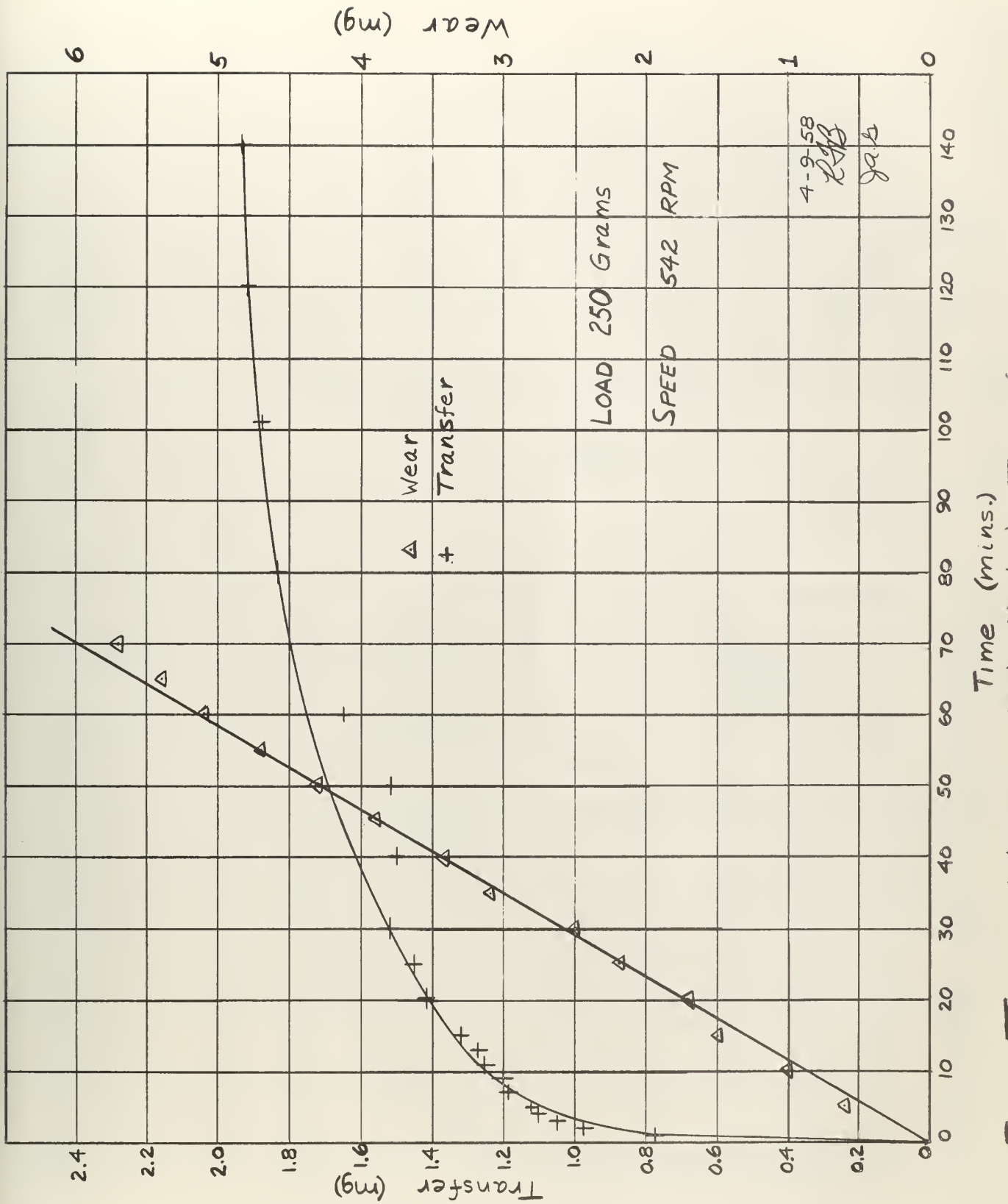


Figure VI. Wear And Metal Transfer

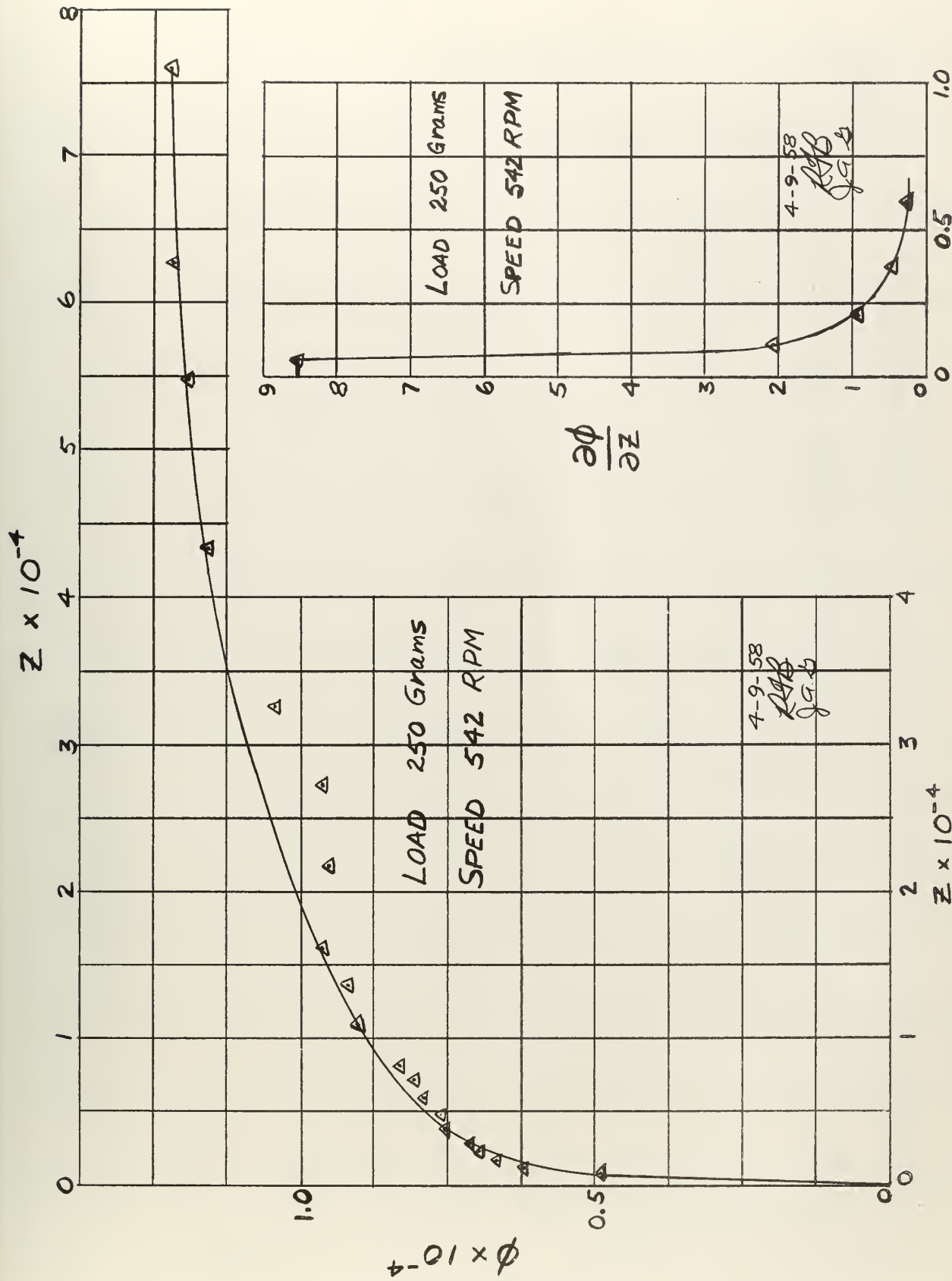


Figure XII. Dimensionless Form of Wear and Metal Transfer

Figure XIII. Slope of Figure XII

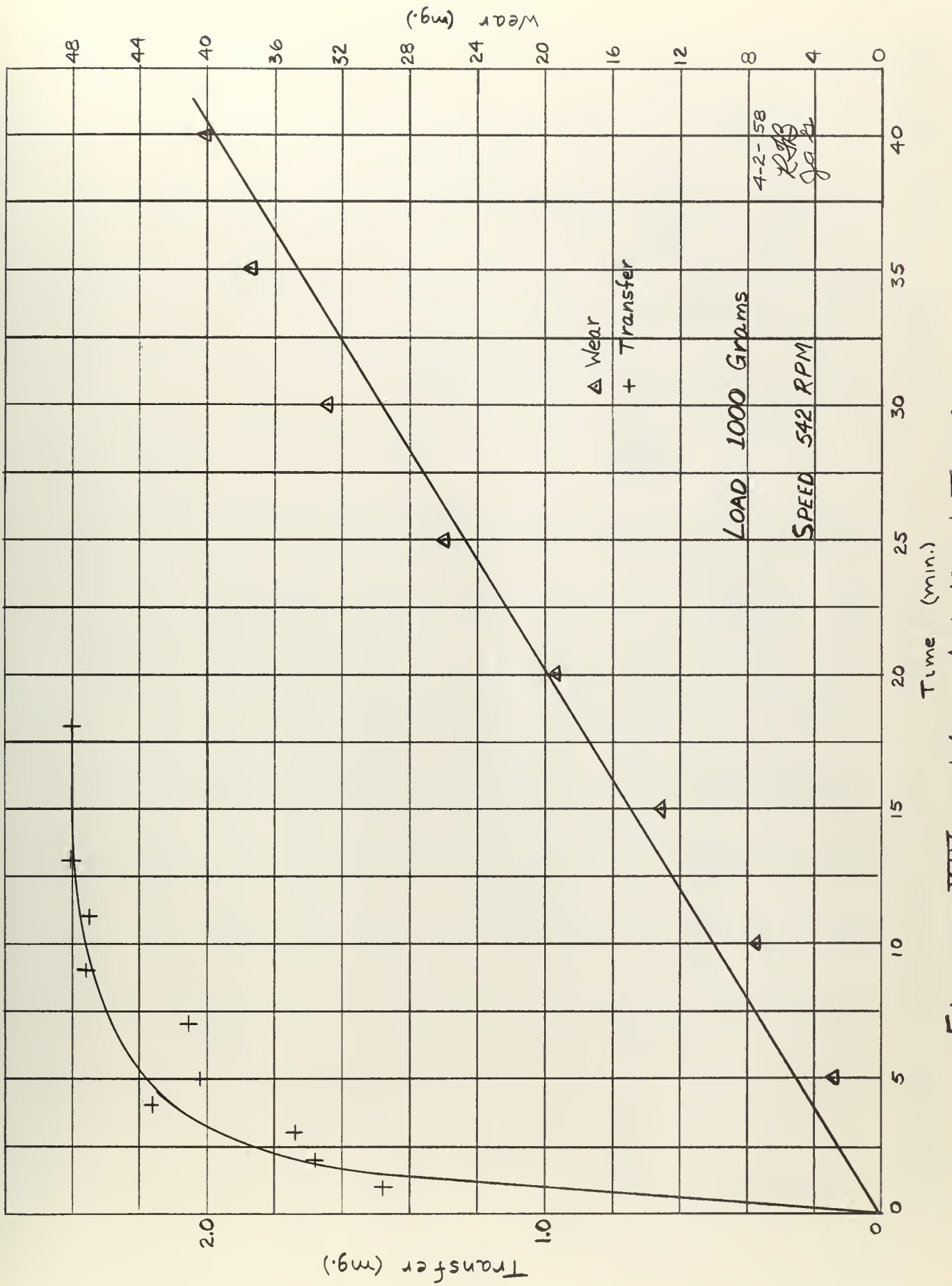


Figure XIV. Wear And Metal Transfer

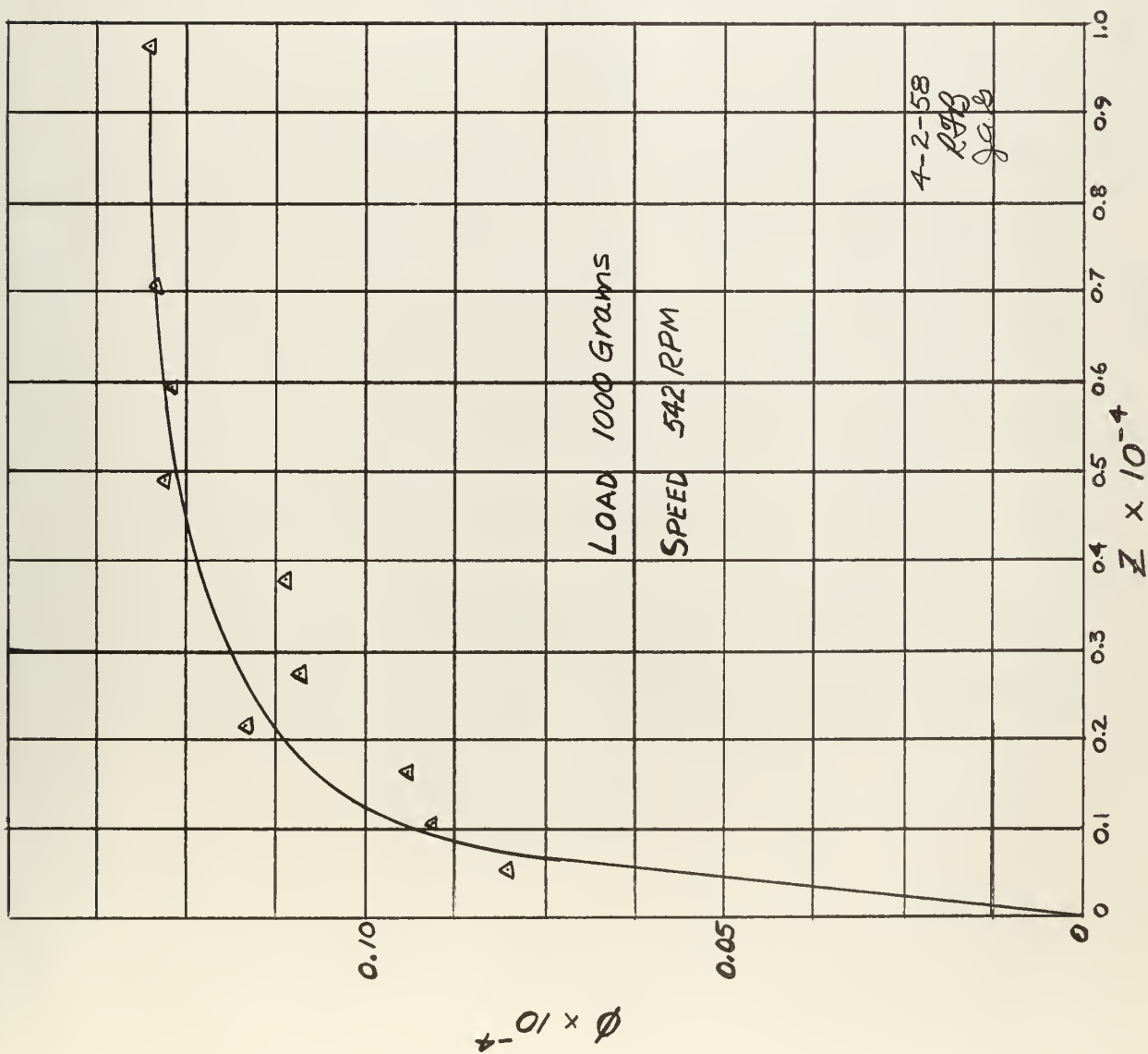


Figure XV. Dimensionless Form of Wear and Metal Transfer

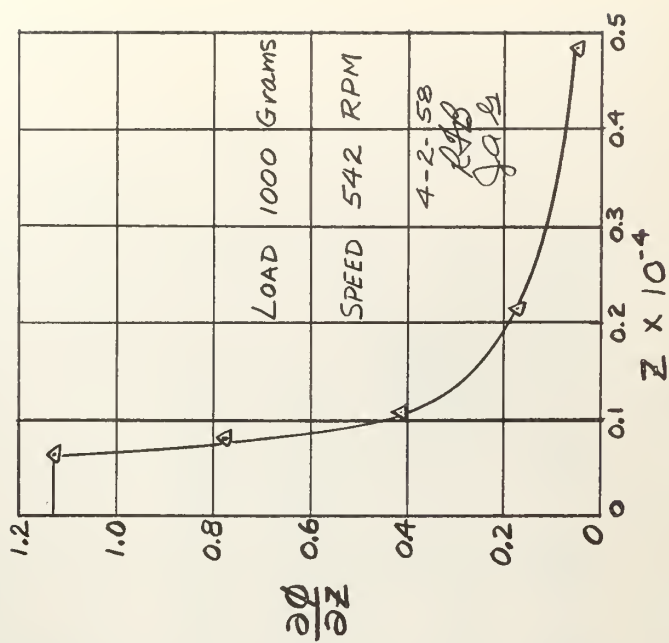


Figure XVI. Slope of Figure XV

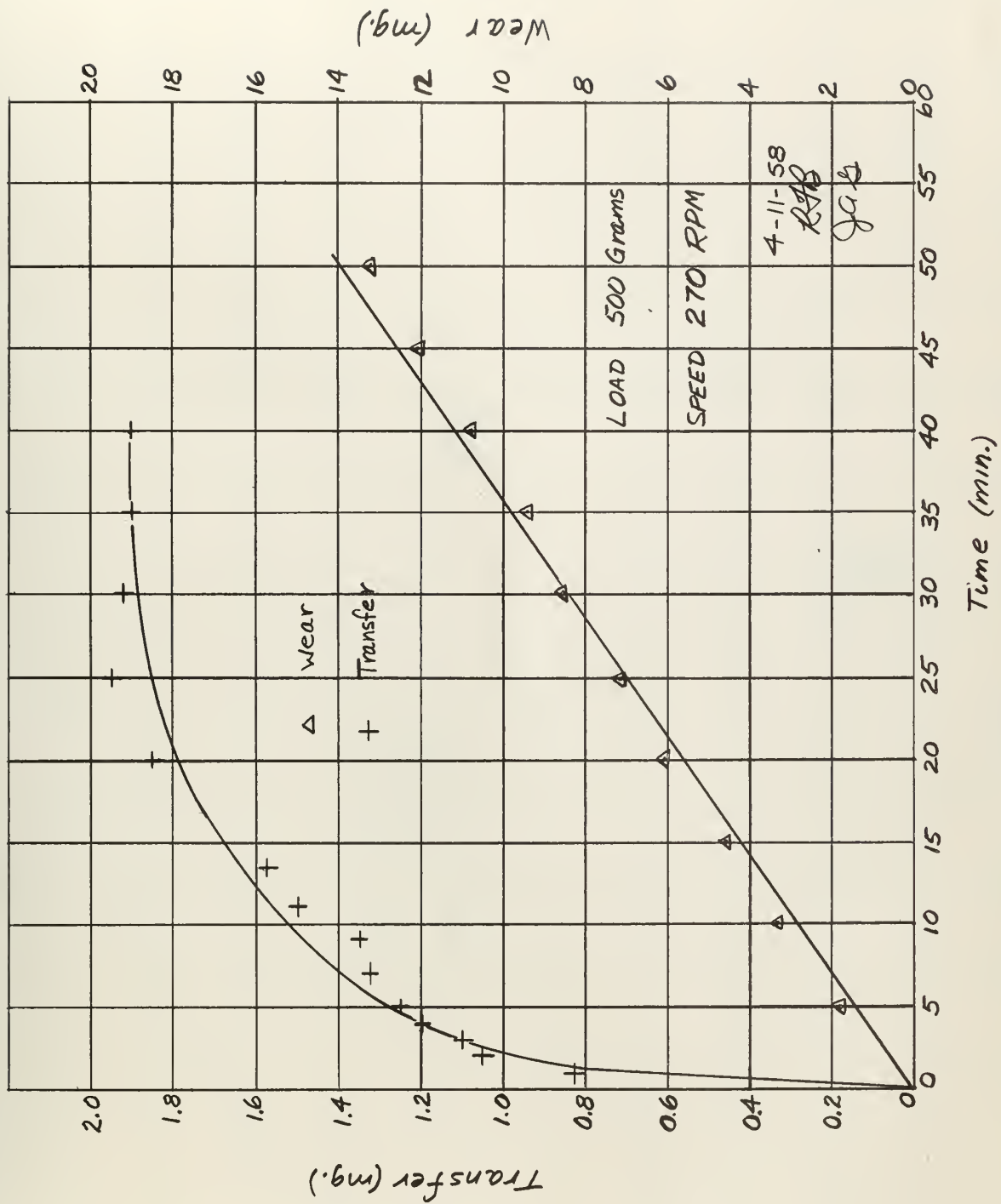


Figure XVII Wear And Metal Transfer

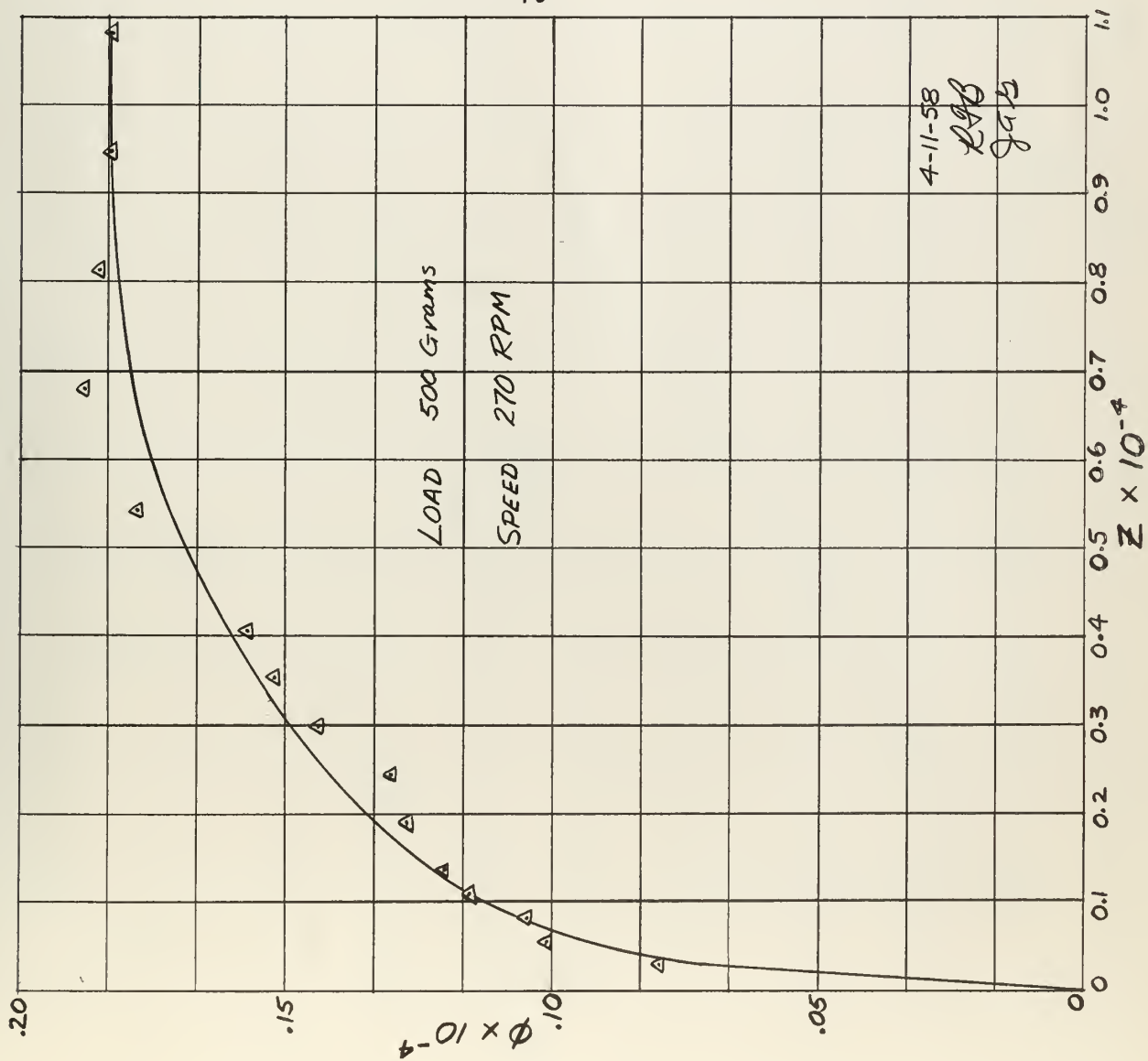


Figure XVIII Dimensionless Form of Wear and Metal Transfer

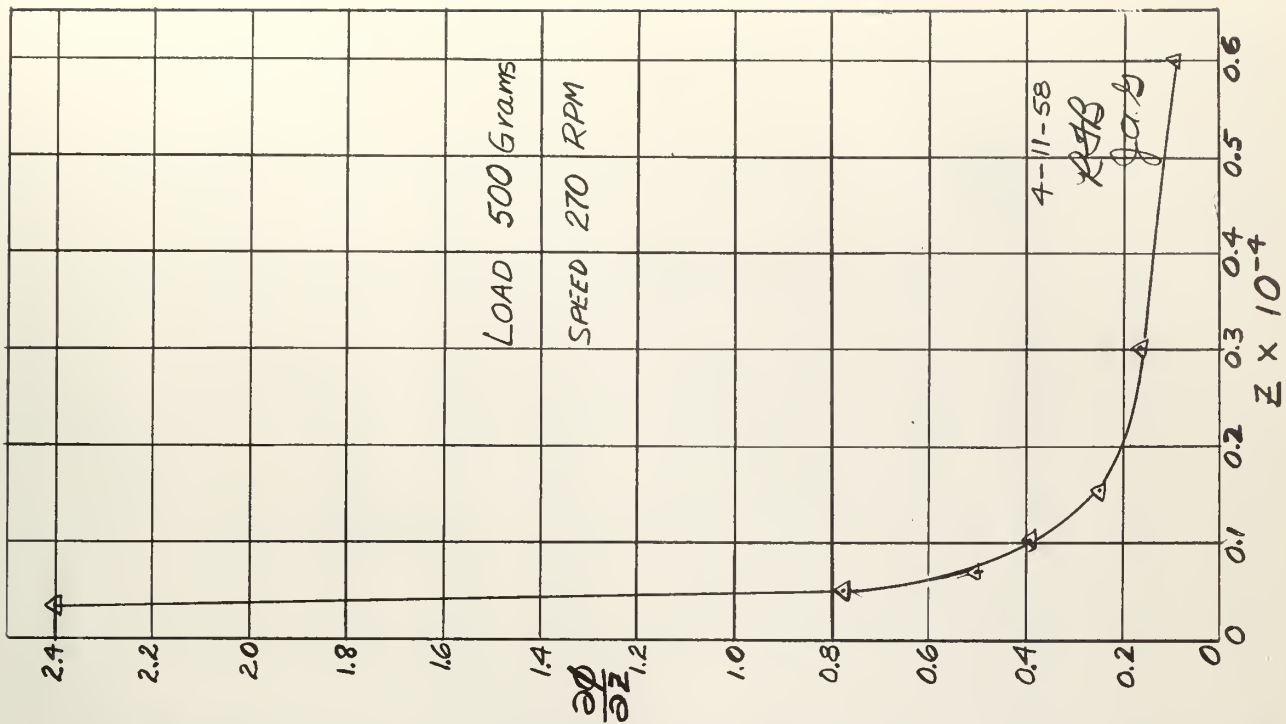


Figure XIX Slope of Figure XVIII

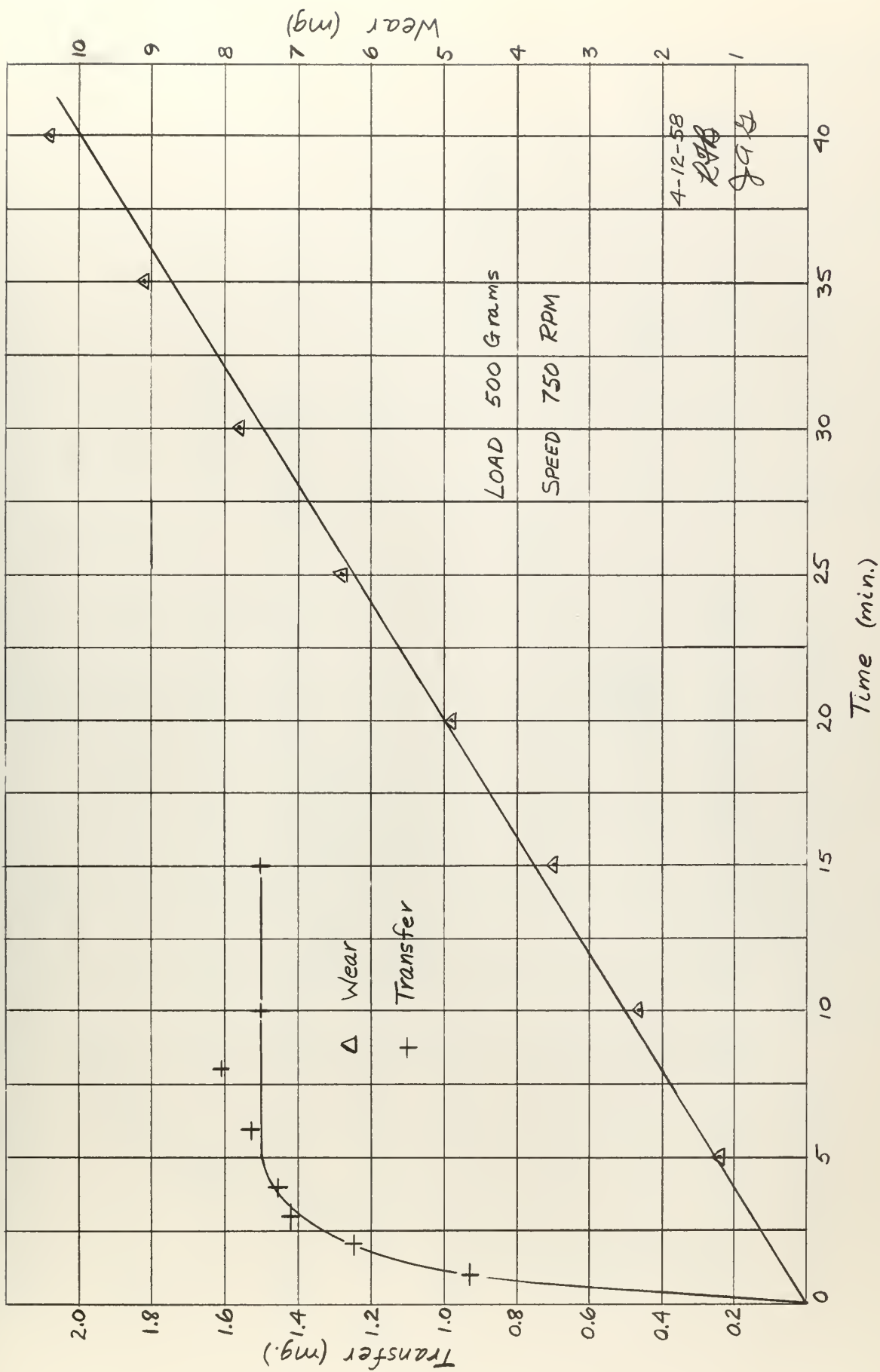


Figure XX Wear And Metal Transfer

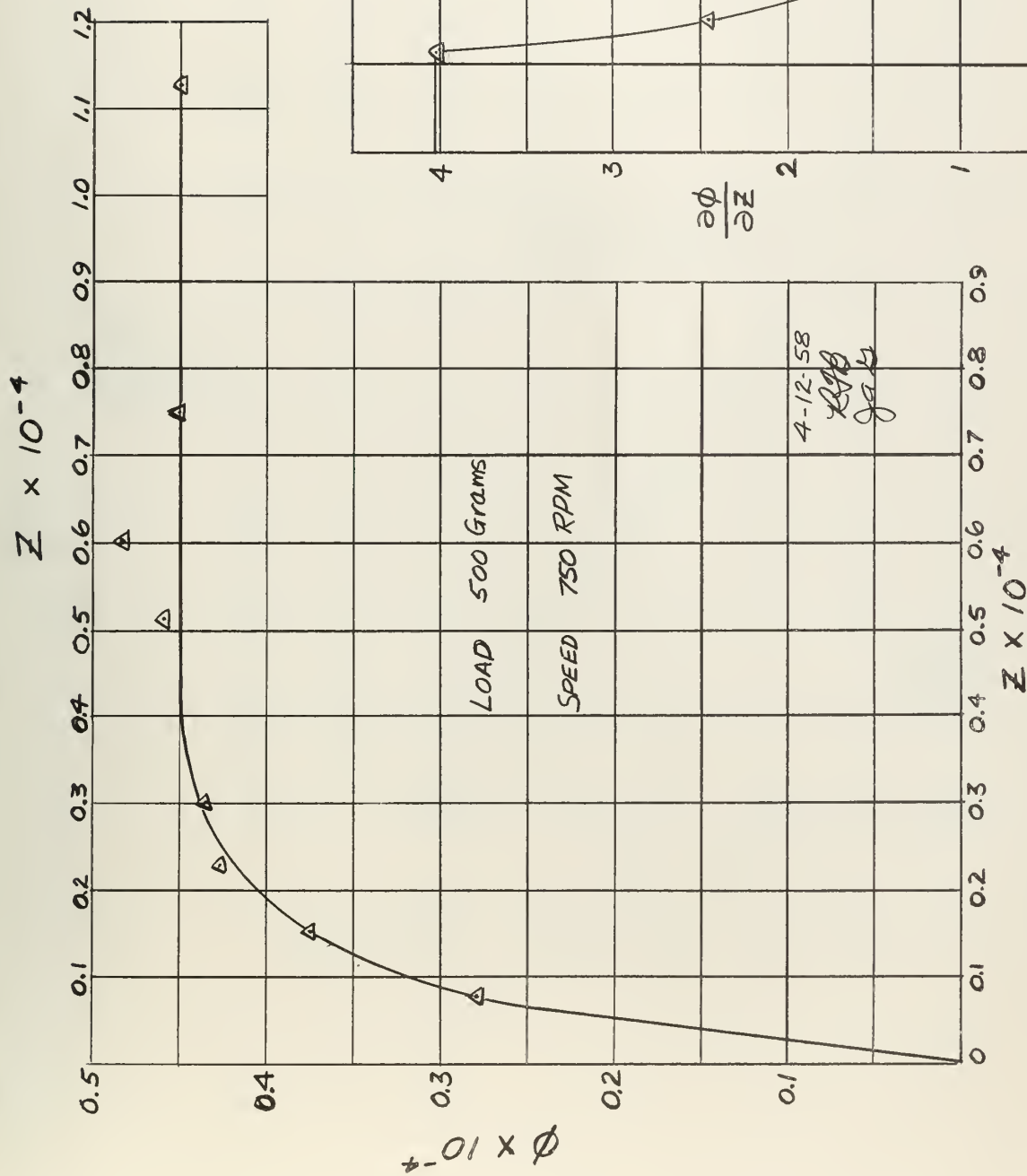


Figure XXI Dimensionless Form of Wear and Metal Transfer.

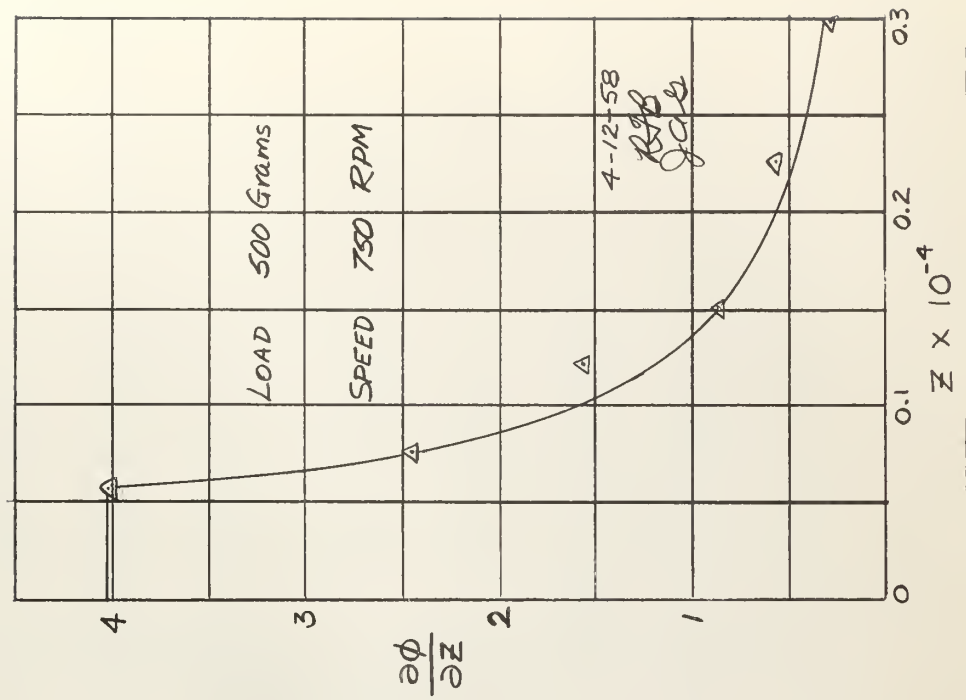


Figure XXII Slope of Figure XXI

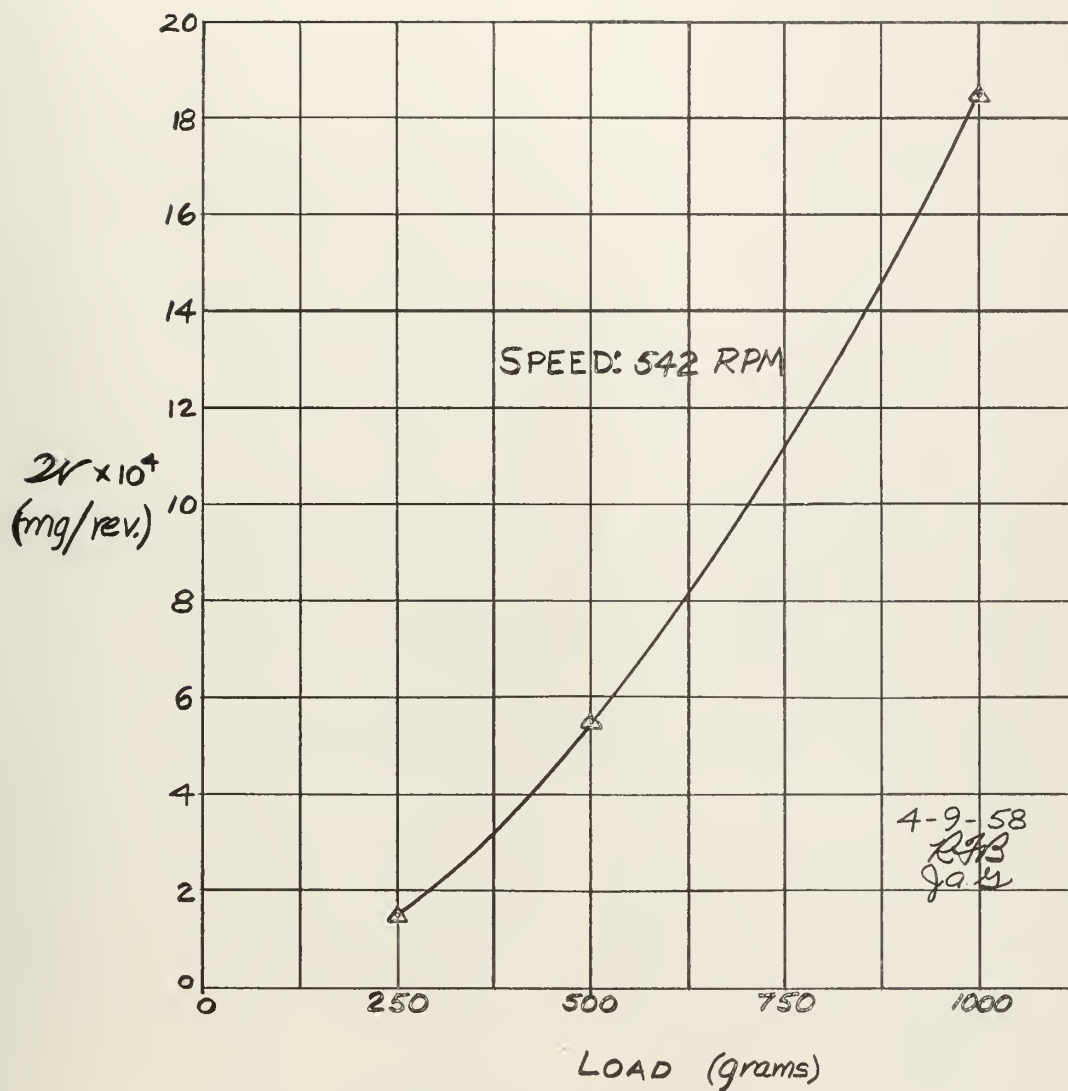


Figure XXIII Wear Rate Vs. Load

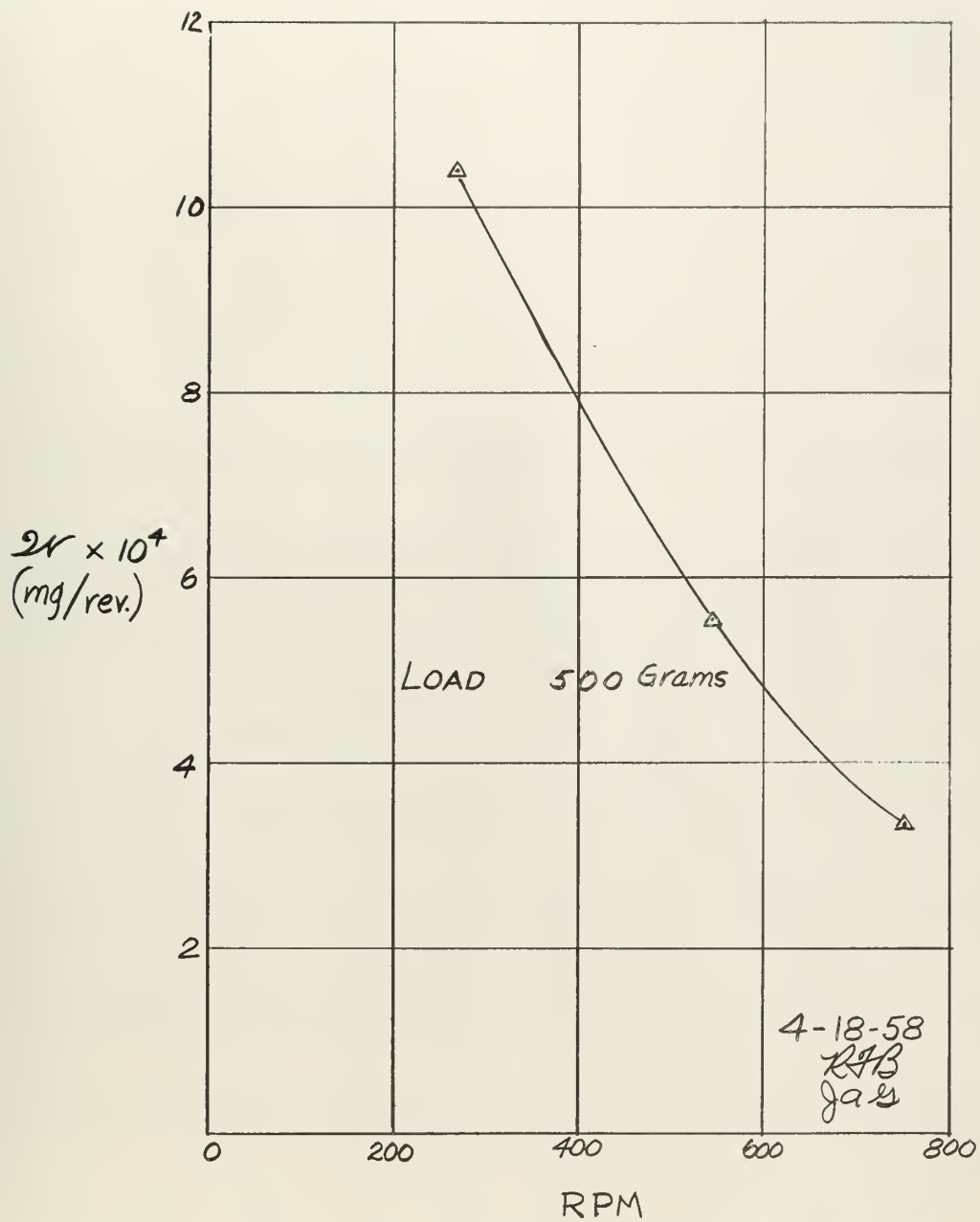


Figure XXIV Wear Rate Vs R.P.M

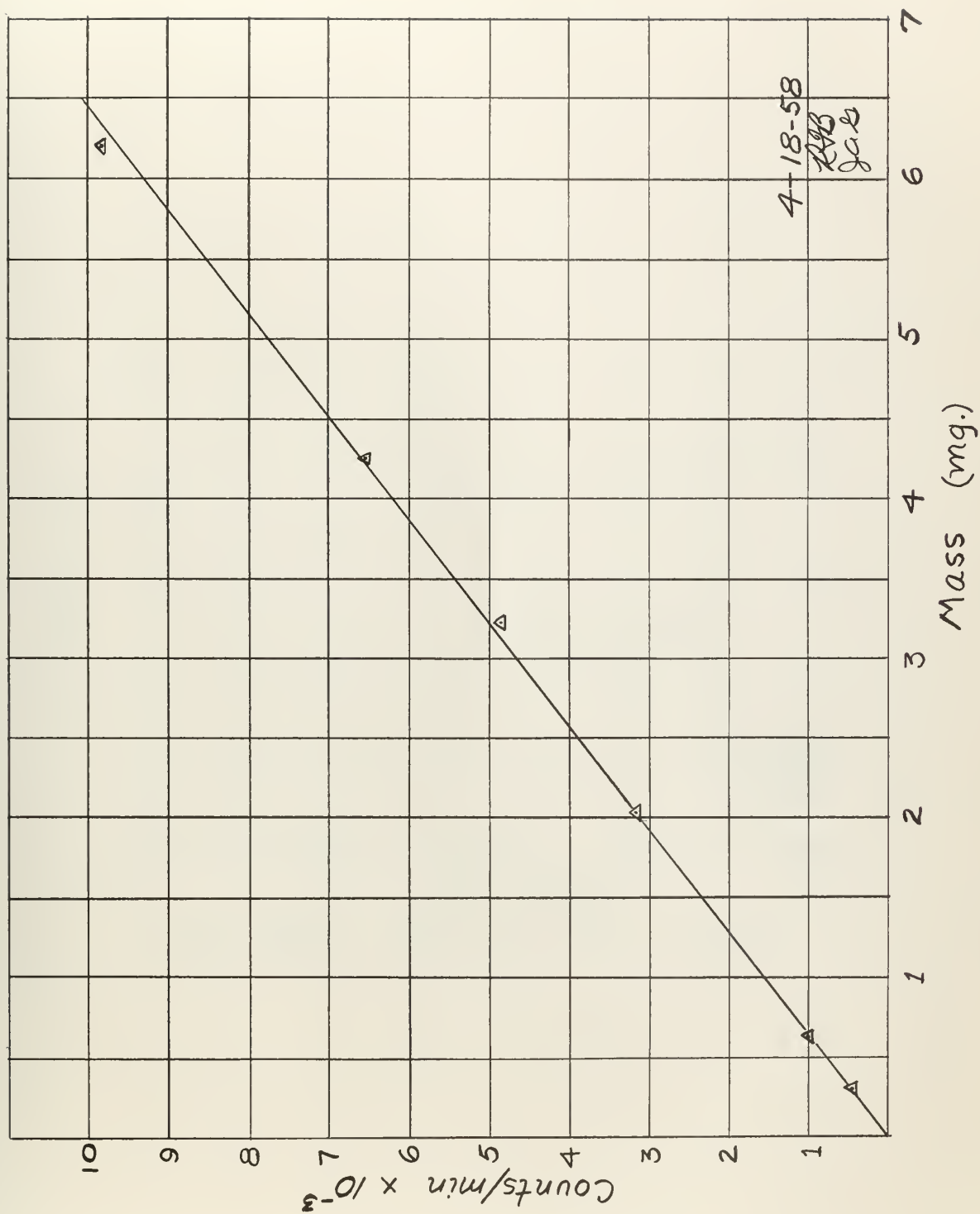


Figure XXV Activity Vs. Mass of Radioactive Standards

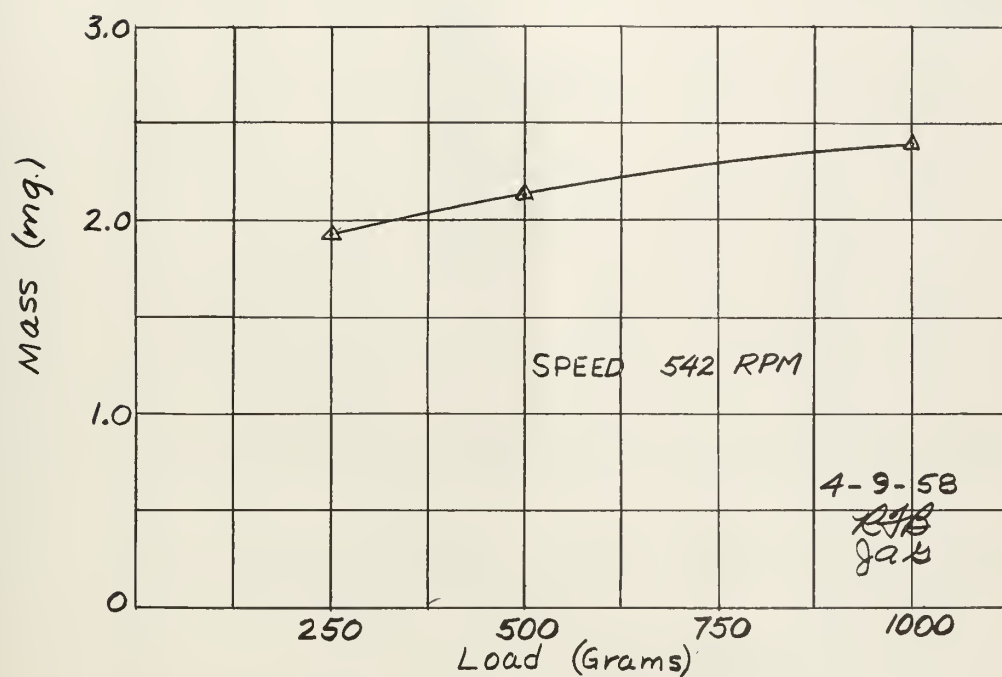


Figure XXVI Equilibrium Mass Vs. Load

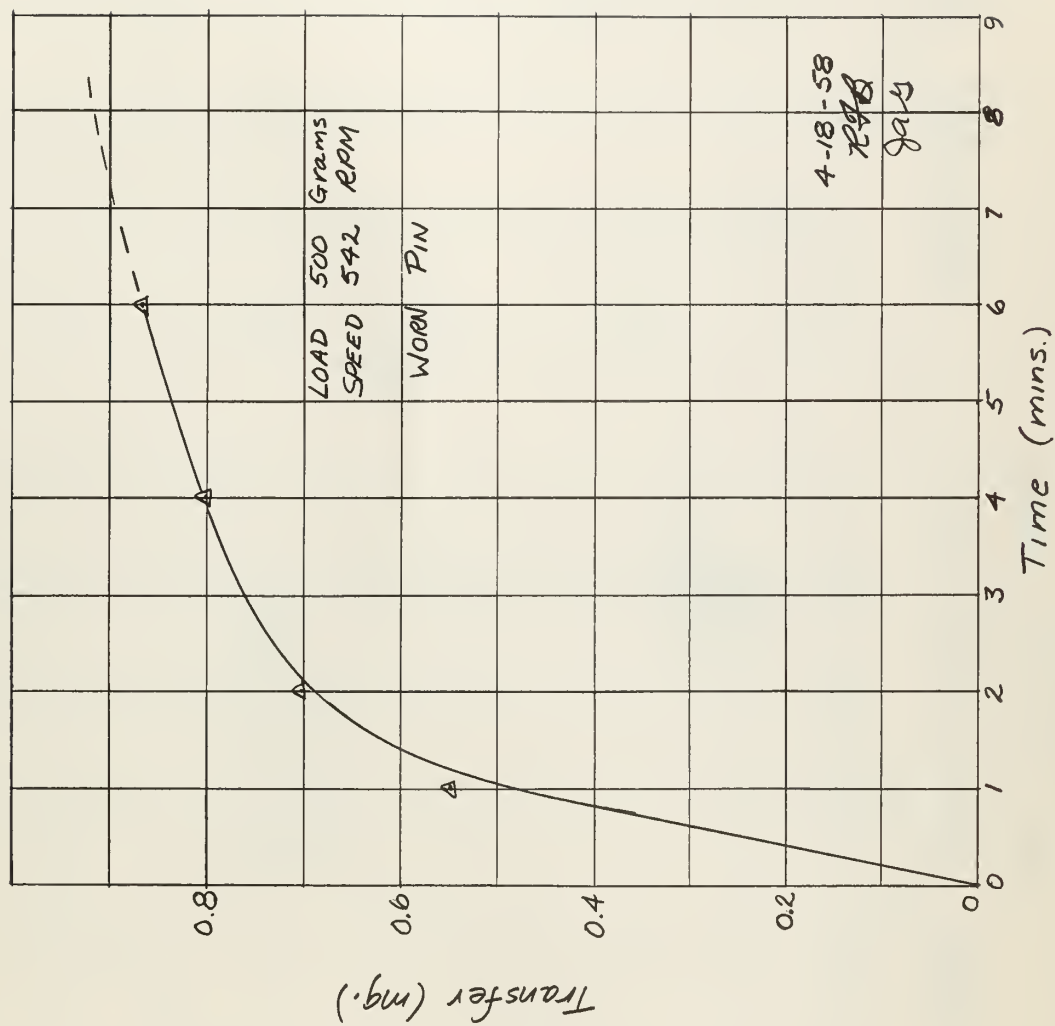


Figure XXVII Metal Transfer

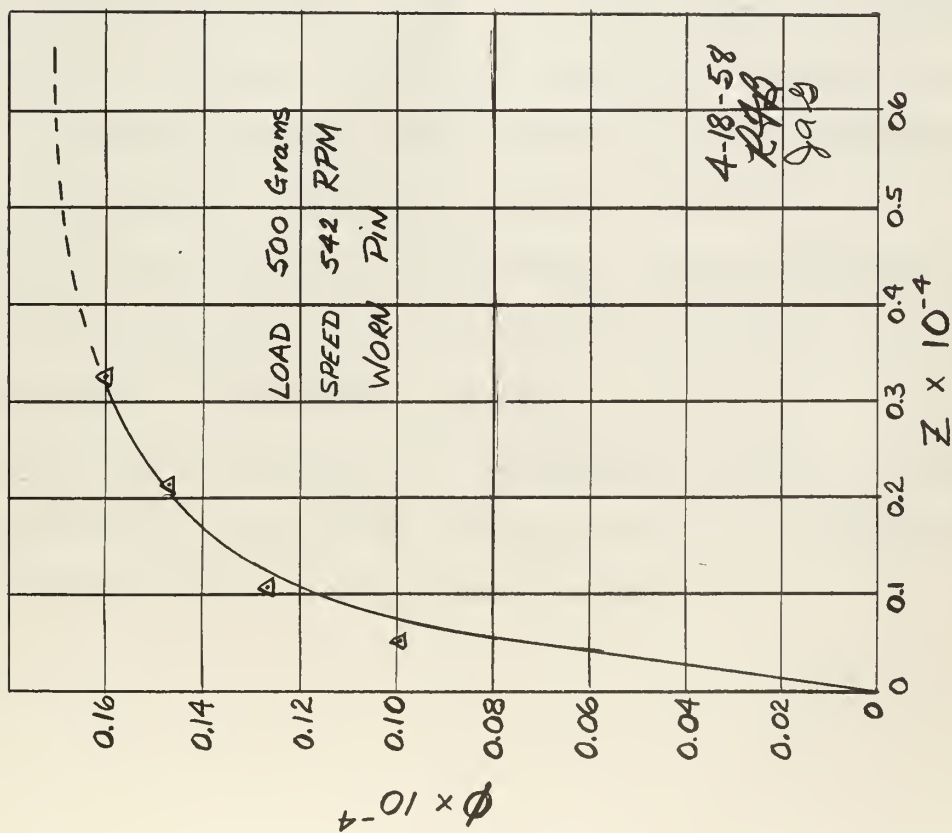


Figure XXVIII Dimensionless Form of
Wear and Metal Transfer

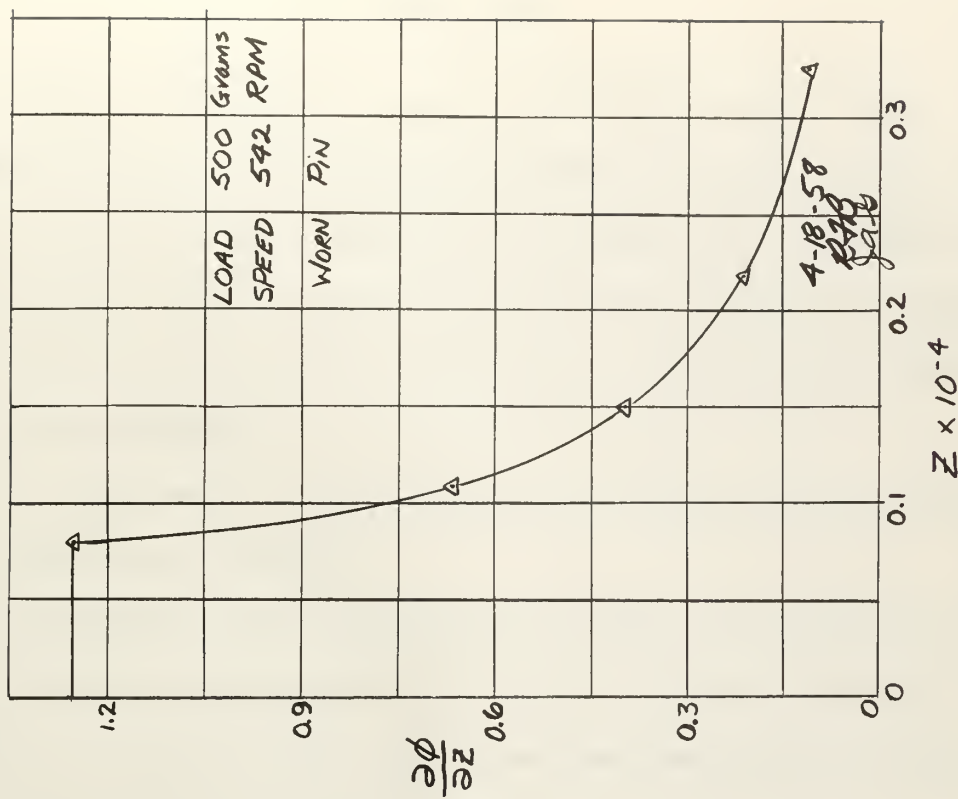


Figure XXIX Slope of Figure XXVIII

IV. CONCLUSIONS

1. These tests corroborated the results found by Kerridge (1955).
However, because of more stringent atmospheric operating conditions, that of dry, oil-free, compressed air, instead of the atmosphere with its possible lubricating qualities and because of different materials, the total wear and total mass transfer and their rates were higher in these experiments.
2. For each test, under constant operating conditions, the wear rate was found to be a constant.
3. Oxidation plays a major role in both the rate of wear from the pin and the rate of mass transfer to the ring. This was verified by varying the length of time between wear measurements, and the speed, in comparing the mass transfer rates.
4. As the speed was increased, a point was reached where the surface temperature of the ring controls the rate of mass transfer to the ring. Above this critical speed, transfer of material was reduced and at 1000 rev/min it was practically nil.
5. Below the critical speed, it was found that, within experimental error, the total amount of mass transferred (equilibrium conditions) was independent of both load and speed.
6. Finally, it was determined that a theoretical statistical analysis of the behavior of the sliding contacts can be used to interpret the experimental results of wear and metal transfer tests.

V. RECOMMENDATIONS

As shown in the last few tests and previously described, the initial wear and transfer rates are dependent on the condition of the contacting face of the pin. A fresh pin, with a polished face, gives higher initial rates than when a test is started with a worn pin. This difference certainly affected the quantitative results of the early tests. Additional tests should be conducted to see whether the utilization of worn pins throughout the experiments will produce results that are in conformance with the theoretical derivation.

Since oxidation is such an important factor in both wear and mass transfer, a series of tests should be conducted in an inert operating atmosphere. This will greatly reduce or eliminate the oxidation process and give additional information about the wear and transfer mechanisms.

In applying these experimental data to the variables of Equation (1), the thickness, (y) , of the transferred layer was obtained indirectly through the mass of the layer. A direct measurement was attempted by use of an interference microscope but since this work was not within the limitations of the equipment, the former method was used. For any future work, a means should be devised to make a direct measurement of thickness.

The mechanism which controls the wear and mass transfer rates both at very high speeds and also under light loads, is at present somewhat obscure. Further investigation in these directions is required.

VI. APPENDIX

APPENDIX A

Establishing the Standard for Comparison with the Test Ring to Denote the Amount of Mass Transfer.

It was realized that the accuracy of the data and therefore the entire experiment depended upon relating the radioactivity of the test ring to that of a standard that had a known amount of active material deposited on it. To eliminate as many sources of error as possible it was agreed to simulate the geometry of the test ring in making the standard.

The first suggestion was a method of electrodeposition using an irradiated pin as one electrode and one of the rings as the other. Since the pins were of mild steel, containing impurities, it was impossible to proceed with this method.

Therefore the system of dissolving the radioactive material and evaporating it in a definite amount along a restricted area simulating the actual area of mass transfer was used. This was done by milling a $\frac{1}{4}$ " x .006" channel in a piece of .015" steel shim stock as shown in Figure VI. This strip fit very tightly around an aluminum ring that has been made to the dimensions of the hardened steel test rings. Attaching and removing the strip was done by springing the ring which had been cut, inserting the tabs of the strip then allowing the ring to close, tightening the strip on the circumference. (Figure VII)

A radioactive pin of known weight was allowed to dissolve partially in a known amount of concentrated hydrochloric acid. Upon weighing the pin after some time, the concentration of the pin material in the solution

was determined. By micrometer pipette a known amount of the solution was deposited on the strip by evenly distributing the liquid along the $\frac{1}{4}$ " channel. Now since a known volume of liquid that had a known concentration, was deposited, the amount of pin material on the strip was calculated. The acid was allowed to evaporate in an enclosed hood. All steps of the procedure were done under controlled conditions to reduce the potential radioactive hazard.

When the liquid had evaporated, the next step was to provide a means of preventing the deposited metal from flaking as the strip was curved around the ring. Four different coverings were tested to determine their energy absorption or shielding of the radioactive material. These were rubber hydrochloride film (thickness .002"), electrical tape, Scotch transparent tape and Krylon dielectric coating. The first three gave reductions in the counts per minute between 15 and 20 per cent while on 11 tests, Krylon gave an average reduction of 6.6 per cent. This correction was provided for in the use of the standards. Krylon, sprayed evenly over the strip, gave a durable coating, allowing the standards to be handled without loss of material from the groove.

The counts per minute received from these standards, when rotated in the same set-up as a test ring, served as a basis for calculating the amount of mass transferred from the pin to the ring during a test.

The activity and the mass should have a linear relationship. For the six standards, each with a different known mass, the relation for a particular day is shown on Figure XXV. Since the radioactivity of these standards was decaying at the same rate as the test pins, the standards were counted and a line drawn as Figure XXV each day a test

run was made.

During the above process a determination of the effect of curving the standard was made. By taking a count on a flat standard and another at the same point after it was curved to a $2\frac{1}{2}$ " diameter, the reduction of counts registered on the counter was approximately 25%. Had the standards remained flat this would have been considered but since the geometry of the standard and the test ring was the same, the correction was unnecessary.

APPENDIX B

Calculation for Required Irradiation of the Test Pins.

The common radioactivity production and decay equation was used:

$$A = \phi \sigma N (1 - e^{-\lambda t}) e^{-\lambda \theta} \quad (3)$$

where:

A ----activity disintegrations/time

ϕ ----flux neutrons/cm² sec

N ----total atoms of the isotope to be irradiated

λ ----disintegration constant $\frac{.693}{\text{half life}}$

t ----time for irradiation

θ ----time after removal from reactor to time of use

In this experiment Fe⁵⁸ was the isotope that was bombarded to form Fe⁵⁹. Of the iron in the material .31% was of the isotope Fe⁵⁸.

With a flux of 1.5×10^{12} irradiating the pins for a period of 5 days it was determined from the above equation that the activity would be .057 mc/gm producing 2115 counts/sec/mg after a delay time, (θ), of 30 days. With a counter efficiency of about 10 per cent, this activity would produce about 12000 counts/min/mg. Introduction of the correction factor for the Krylon covering, reduced this to a count that was in the range where the background count was insignificant and the actual count was indicative of the mass transferred.

APPENDIX C

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